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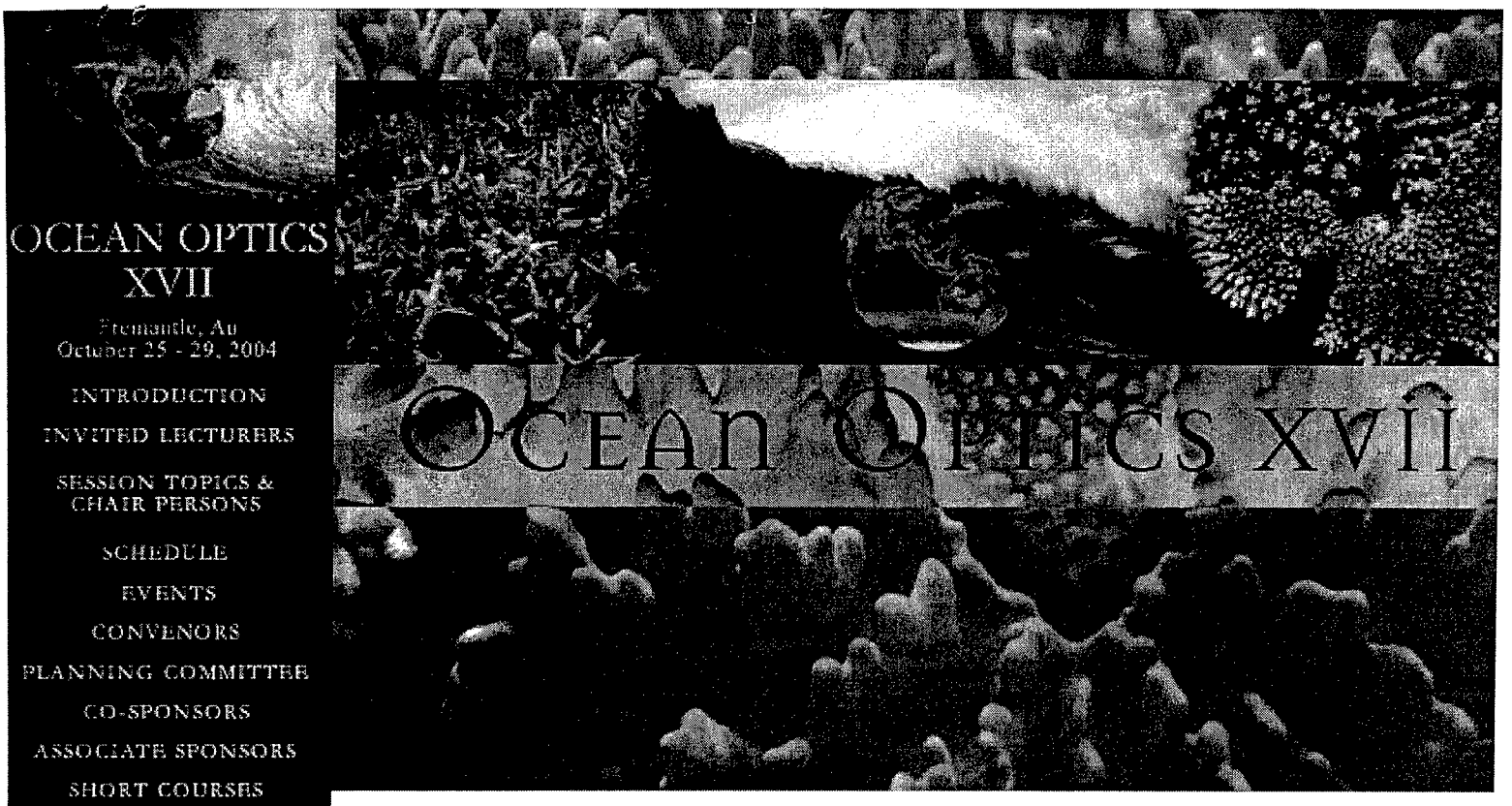

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Application of a Near-Infrared Slope Algorithm to Derive Optical Properties from High-Resolution, Hyperspectral Aircraft Imagery

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ABSTRACT

Using new algorithms, we derive estimates of partitioned absorption (a) and scattering (b) coefficients from high-resolution, hyperspectral aircraft imagery collected with the PHILLS sensor. During May 2002, we conducted simultaneous ship and aircraft surveys in a dynamic environment in the northern Gulf of Mexico (coastal waters near Mobile Bay, Alabama). Optical measurements included hyperspectral remote sensing reflectance (R_{rs}), partitioned absorption coefficients (phytoplankton, detrital, and colored dissolved organic matter components), beam attenuation (c), backscattering (b_b) coefficient, HPLC phytoplankton pigment concentrations, and organic/inorganic particle loads. Our objectives are to: (1) develop new algorithms to estimate optical properties from hyperspectral ocean color imagery; (2) apply the algorithms to high-resolution aircraft imagery to characterize the spatial optical variability in an environment impacted by high concentrations of dissolved and particulate materials; and (3) perform an optical water mass classification on the aircraft imagery. The new optical classification system based on the partitioned absorption coefficients is used to distinguish water masses and track coastal features.

The PHILLS radiance values are first converted to atmospherically-corrected reflectances through an empirical line calibration technique that couples the imagery with in situ reflectance measurements. Then, by focusing initially on the near-infrared (NIR) region of the reflectance spectrum where absorption is dominated by pure water, we can estimate the backscattering coefficient at 715 nm by solving a quadratic equation. A linear model extends this estimate spectrally to shorter wavelengths. From reflectance and backscattering we subsequently estimate the total absorption coefficient. Empirical relationships based on filter pad measurements are used to partition the total absorption into phytoplankton, detrital, and CDOM components, as well as organic and inorganic particulate loads. Finally, we compare the aircraft-derived estimates with in situ optical measurements collected during the coincident ship surveys, and assess errors.

INTRODUCTION

Remote sensing imagery can provide synoptic snapshots of water optical properties. Airborne imagery generally provides increased spectral and spatial resolution compared to satellite imagery (Hyperion is the only hyperspectral satellite sensor currently on orbit (220 channels, 30 m ground resolution, 16-day repeat cycle), but it was launched by NASA as a demonstration project with a one-year on-orbit design lifetime, and it does

not provide operational data). In addition, the temporal resolution of the aircraft imagery (repeat coverage) is only limited by flight requirements and cost constraints, not by orbital paths and times. Thus, shorter temporal and spatial scales (i.e., higher frequency processes such as tidal variability) can generally be resolved with aircraft imagery.

However, aircraft imagery is also fraught with problems unique to that platform. For example, because the sensor is flown at variable heights within the atmospheric layer, rather than above it as is the case for satellite sensors, the atmospheric correction problem is more difficult, particularly over coastal areas. The platform itself is also less stable than a satellite; the aircraft data require roll, pitch, and yaw corrections for accurate ground pixel locations. Instrument calibration is an ongoing issue for any optical sensor that is operated in a harsh environment, such as the constantly vibrating and jarring conditions within an airplane. These difficulties represent challenges that must be overcome before high-quality data are available for incorporation into bio-optical algorithms.

OBJECTIVES

Our objectives are to: (1) develop new algorithms to estimate optical properties from hyperspectral ocean color imagery; (2) apply the algorithms to high-resolution aircraft imagery to characterize the spatial optical variability in an environment impacted by high concentrations of dissolved and particulate materials; and (3) perform an optical water mass classification on the aircraft imagery.

METHODS

In May 2002, we conducted field experiments near Mobile Bay, Alabama, to characterize the coastal optical properties using ship, satellite, and aircraft data. A total of 63 stations were occupied by two ships over an eight-day period. One ship, the R/V Pelican, mapped the outflow plume from Mobile Bay while the other vessel, the R/V Ocean Color, examined spatial variability of optical properties in Mobile Bay and Mississippi Sound (shoreward of the barrier islands). *In situ* optical measurements included hyperspectral remote sensing reflectance (ASD and Spectrex instruments), absorption and beam attenuation coefficients (and scattering coefficient by difference; ac9 instrument), backscattering coefficient (Hydroscat instrument).

In addition, whole water samples were collected on both ships. Filter pad absorption analyses were performed using the ASD fiber optic spectroradiometer to partition the total absorption coefficient into phytoplankton (a_ϕ), detrital (a_d), and colored dissolved organic matter (gelbstoff, a_g) components. GF/F filtered samples were also collected and frozen in liquid nitrogen for subsequent fluorometric and HPLC pigment analysis. Total suspended solids (TSS), particulate inorganic matter (PIM), and particulate organic matter (POM) were determined gravimetrically. Prior to the cruise, 47 mm GF/F filters were rinsed three times with Milli-Q water, dried for two hours at 103° C, ashed for 15 minutes at 550° C, weighed on an analytical scale, and stored for analysis in small, labeled plastic petri dishes. During the experiment, whole water samples were

subsequently filtered through the prepared filters, rinsed thoroughly, dried, and weighed to determine TSS in mg/l. The filters were then ashed and re-weighed to determine PIM (and POM through subtraction).

Coincident aircraft imagery was collected with the Portable Hyperspectral Imager for Low-Light Spectroscopy (PHILLS). Four flight days were successfully completed with 4-8 overlapping flight lines per day oriented parallel to the coast (into or away from the sun) to allow image mosaicking with minimal sun glint. PHILLS operated with 220 spectral bands at a flight altitude of 10,000 m to yield a 10 m ground pixel spatial dimension. Figure 1 shows an example of the flight lines and times, as well as the coincident ship stations and collection times, for 21 May, 2002. Similar figures for flights on 19, 20, and 23 May are not shown.

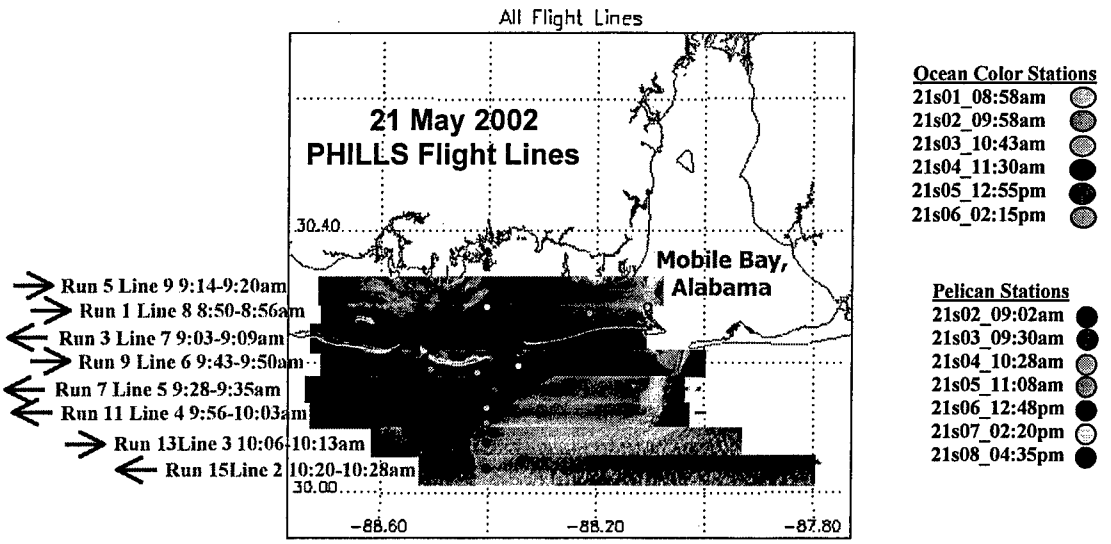

Figure 1. Locations and times of flight lines and ship stations, 21 May, 2002.

The geolocated, calibrated radiance data (Kohler, 2002) were subsequently converted to remote-sensing reflectancs (R_{rs}) using an empirical line calibration (ELC) technique (Moran et al., 2001). This approach simultaneously applies an atmospheric correction to the imagery by forcing the aircraft radiance data to match the *in situ* R_{rs} data. Following the ELC, a near-infrared (NIR) slope algorithm was applied to the imagery to derive estimates of inherent optical properties and chlorophyll. The NIR algorithm is described below. Following application of the NIR algorithm, the imagery was goecorrected and mosaicked. Optical property values were then extracted from the imagery at the locations of the ship stations and compared to the measured values. The steps are outlined in Figure 2.

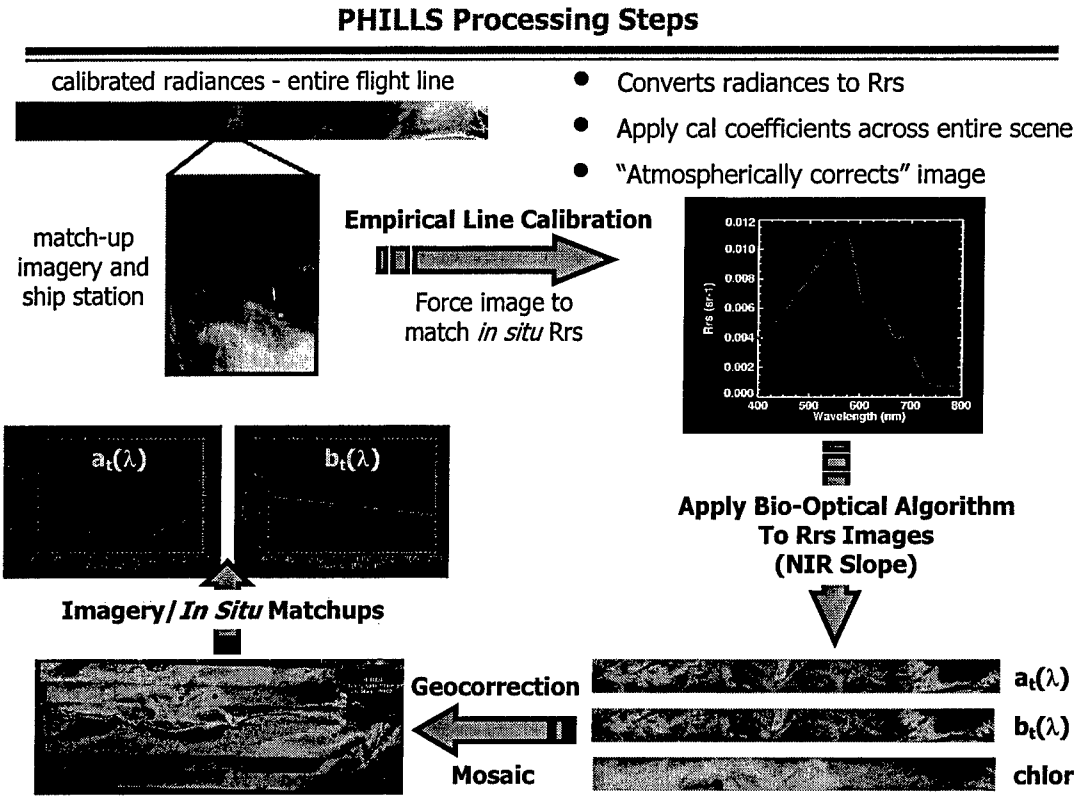

Figure 2. Schematic of processing steps for PHILLS aircraft imagery.

The ELC technique applies constant calibration coefficients across the flight line (and in this case across multiple flight lines) and thus may not be as desirable as an atmospheric model-based correction scheme such as ATREM or TAAFKA (Gao et al., 2000). However, the model-based corrections require some knowledge (or estimate) of several atmospheric properties, such as ozone thickness, aerosol optical depth, relative humidity, etc., and our experience with those approaches is that they often yield unreliable results and/or negative radiances in coastal waters, so we explored the ELC approach.

As mentioned above, we used a single station/flight line combination to derive the calibration coefficients applied to all flight lines on a single day. This approach does not, however, account for bidirectional reflectance differences between the flight lines (east-to-west flight orientation vs. west-to-east orientation; Figure 1), so some banding artifacts remain in the final products at the junctures of the flight lines (Figure 2, chlorophyll mosaic).

Prior to an ELC, we first selected a coastal flight line with a ship station that was collected close in time. For example, on 21 May, we extracted the spectral PHILLS radiance values from run1, line 8 at the location of R/V Ocean Color station 1 (see Figure 1). This flight line of data was collected from 0850 – 0856 local time and the ship station

was occupied at 0858. We then applied the ELC technique to derive calibration coefficients to convert the image radiances to the ship-measured R_{rs} values. This forces the PHILLS and ship R_{rs} spectra to match exactly at that single point in the image. These coefficients were subsequently applied to each pixel in the flight line, and to each flight line for that day. Comparisons between ELC-calculated and ship-measured R_{rs} spectra agreed well at independent stations not used to derive the coefficients (Figure 3), so we adopted the ELC approach for all PHILLS imagery.

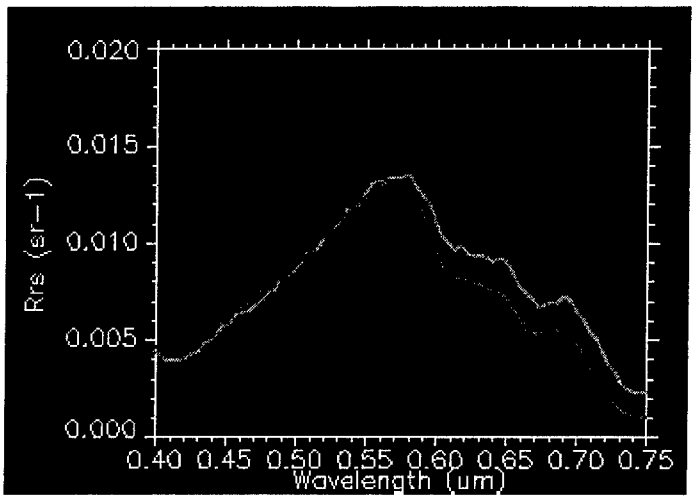

Figure 3. Comparison of ship-measured Rrs (red line) and ELC-derived PHILLS Rrs (green line), for R/V Ocean Color station 3 on 20 May, 2002.

We also explored the effect of different flight line/station combination pairs on the calculated calibration coefficients and resulting derived optical products. On three of the days, several flight line/station combinations were selected for ELC to develop different sets of calibration coefficients. The coefficients were subsequently applied to the imagery, and the agreement between PHILLS-derived and ship-measured absorption and scattering coefficients was used to evaluate the coefficients and select the best set. For example, on 21 May, we evaluated two other potential flight line/station combinations (run 5, line 9 and R/V Ocean Color station 4; run 9, line 6 and R/V Ocean Color station 5). However, the errors between the derived and measured spectral optical properties were larger than with the original calibration coefficients. In general, the different flight line/station combinations used in the ELC did not have as large an impact on the resulting optical estimates as might have been expected (results not shown).

NIR SLOPE ALGORITHM (CALCULATING a AND b_b)

Following application of the ELC to the PHILLS imagery, a NIR slope algorithm was applied to the R_{rs} spectra at each image pixel, to derive the optical properties of the water. The NIR algorithm is based on the observation that the total absorption in the 715 – 735 nm wavelength range is controlled by pure-water absorption (i.e., the absorption by the other components such as phytoplankton, detritus, and CDOM is minimal). Furthermore,

we assume that the spectral shapes of b and b_b are linear and relatively flat over this narrow wavelength range (only a 2.8% difference in b(715) and b(735), based on the spectral model of Gould et al., 1999), and that the C term below is constant ($C = (t^2*f) / (n^2*Q) = 0.051$). These assumptions allow calculation of the backscattering coefficient at 715 nm from the corrected R_{rs} values, and subsequently spectral backscattering and absorption over the entire 400 – 700 nm range. The calculations are summarized below.

Based on $R_{rs} = C\, b_b / (a+b_b)$ (Gordon et al., 1988))
Subscript 1 denotes $\lambda = 715$ nm, subscript 2 denotes $\lambda = 735$ nm
a_{w1}, pure-water absorption at 715 nm = 1.007
a_{w2}, pure-water absorption at 735 nm = 2.39
$b_{b2} = 0.97234\, b_{b1}$

First, calculate the reflectance difference at two NIR wavelengths:

$$R_{rs1} - R_{rs2} = Cb_{b1}/(a_{w1} + b_{b1}) - Cb_{b2}/(a_{w2} + b_{b2}) \qquad (1)$$

Then, substitute and rearrange terms:

$$0.97234 b_{b1}^{\,2} + \left[0.97234 a_{w1} + a_{w2} - C\left(a_{w2} - 0.97234 a_{w1}\right)/\left(R_{rs1} - R_{rs2}\right)\right] b_{b1} + a_{w1} a_{w2} = 0 \qquad (2)$$

Solve the quadratic for the backscattering coefficient at 715 nm, b_{b1}:

$$b_{b1} = \left(-B - \sqrt{B^2 - 9.362}\right)/1.945 \qquad (3)$$

where B is the term in brackets in equation 2.
Next, calculate spectral $b_b(\lambda)$:

$$b_b(\lambda) = b_{b1} \times b_b shape(\lambda) \qquad (4)$$

$$\text{where } b_b shape(\lambda) = \left(1.62517 - 0.00113\lambda\right)/0.817220 \qquad (5)$$

from the spectral model of Gould et al. (1999).
Convert $b_b(\lambda)$ to $b(\lambda)$:

$$b(\lambda) = 53.56857 \times b_b(\lambda) + 0.00765 \qquad (6)$$

also from Gould et al. (1999).
Finally, calculate total absorption, $a_T(\lambda)$:

$$a_T(\lambda) = Cb_b(\lambda)/Rrs(\lambda) - b_b(\lambda) \qquad (7)$$

OPTICAL WATER MASS CLASSIFICATION ALGORITHMS (PARTITIONING a AND b INTO COMPONENTS)

Following calculation of a, b_b, and b, the scattering coefficient is partitioned into organic and inorganic components and the total absorption coefficient is partitioned into phytoplankton, detrital, and CDOM components, using empirical relationships. In addition, we require estimates of chlorophyll (here we use the Stumpf et al. (2000) algorithm) as well as $a_\varphi(443)$ derived from the chlorophyll value (Stumpf et al., 2003). The algorithm steps can be summarized as follows:

1. Calculate the organic component of scattering at 660 nm, $b_o(660)$, from chlorophyll (Loisel & Morel, 1998)
2. Calculate $b_o(555)$ from $b_o(660)$
3. Calculate the inorganic component of scattering at 555 nm, $b_i(555) = b(555) - b_o(555)$
4. Calculate $a_d(412)$ from $b_i(555)$
5. Calculate total absorption minus water absorption, $a_{T\text{-}W}(\lambda) = a_T(\lambda) - a_W(\lambda)$
6. Calculate spectral phytoplankton absorption, $a_\varphi(\lambda)$, from $a_\varphi(443)$
7. Calculate combined detrital and CDOM absorption, $a_{dg}(\lambda) = a_{T\text{-}W}(\lambda) - a_\varphi(\lambda)$
8. Calculate CDOM absorption at 412 nm, $a_g(412) = a_{dg}(412) - a_d(412)$
9. Calculate $a_g(\lambda)$ from $a_g(412)$
10. Calculate $a_d(\lambda) = a_{dg}(\lambda) - a_g(\lambda)$
11. Calculate particulate absorption $a_p(\lambda) = a_\varphi(\lambda) + a_d(\lambda)$
12. Calculate PIM from $a_p(412)$
13. Calculate POM from $a_p(443)$
14. Calculate TSS = PIM + POM

See Gould et al. (2002) for equations, references, and further details on calculating organic scattering (b_o), $a_d(412)$, $a_g(\lambda)$, PIM, and POM.

RESULTS

After applying the ELC, chlorophyll, and NIR bio-optical algorithms, we combine the daily flight lines to create image mosaics of the region, for each of the optical products. PHILLS and SeaWiFS chlorophyll images covering roughly the same area of Mississippi Sound near Mobile Bay for May 20 are shown in Figure 4. The same chlorophyll algorithm was applied to both images, and the color scales are identical. Although the PHILLS imagery is at much higher spatial resolution, the close agreement between the two images, in both magnitude and pattern, indicates that the R_{rs} values resulting from the ELC must also be in close agreement with the SeaWiFS R_{rs} values.

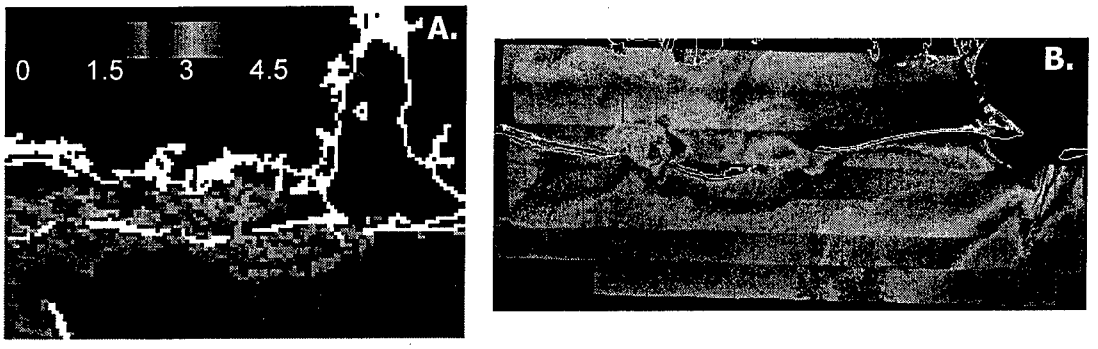

Figure 4. Chlorophyll concentration, 20 May, 2002. A. SeaWiFS. B. PHILLS

Mosaics of organic and inorganic scattering coefficients, CDOM, detrital, and phytoplankton absorption coefficients, PIM, and POM, for 21 May are shown in Figure 5. Note the different scales and units. The scattering coefficients due to inorganic matter are in general an order of magnitude larger than the organic ones, although concentrations of particulate inorganic matter are only 2-3 times larger than concentrations of particulate organic matter. Also, the phytoplankton absorption coefficients are about 6 times lower than those due to CDOM and detritus, and the distribution is more dispersed.

Comparisons of PHILLS-derived and ac9-measured spectral absorption and scattering coefficients from R/V Ocean Color station 1 on 21 May are shown in Figure 6. This station was used to perform the ELC, so the PHILLS Rrs spectrum matches the ship measurements exactly. The strong agreement between the PHILLS and ac9 values at this station where the atmospheric correction was "perfect", particularly for the scattering coefficient, indicates the efficacy of the NIR slope algorithms. A non-constant spectral shape for the C term in equation 1, or variability in the b_b/b ratio could contribute to the discrepancy between the derived and measured absorption values. Calculations of error statistics for all coincident ship and aircraft values are in progress.

We use the partitioned absorption components in an optical water mass classification scheme to characterize the region. The percentages of total absorption due to $a_d(412)$, $a_g(412)$, and $a_\varphi(443)$ form the three axes in a ternary diagram, to quantitatively illustrate the dominant absorbing species at each image pixel. Because we are using absorption percentages, we are looking at relative changes in the dominant absorbing characteristics at each pixel rather than changes in absolute magnitude of the absorption coefficients. Thus the patterns show compositional changes. The optical classification scheme allows us to examine spatial and temporal optical variability, as well as follow features and track water masses. Figure 7 shows an example of this approach applied to the 19 May PHILLS imagery. Red pixels in the RGB composite mage indicate relatively higherdetrital absorption, green pixels indicate relatively higher phytoplankton absorption, and blue pixels indicate relatively higher CDOM absorption.

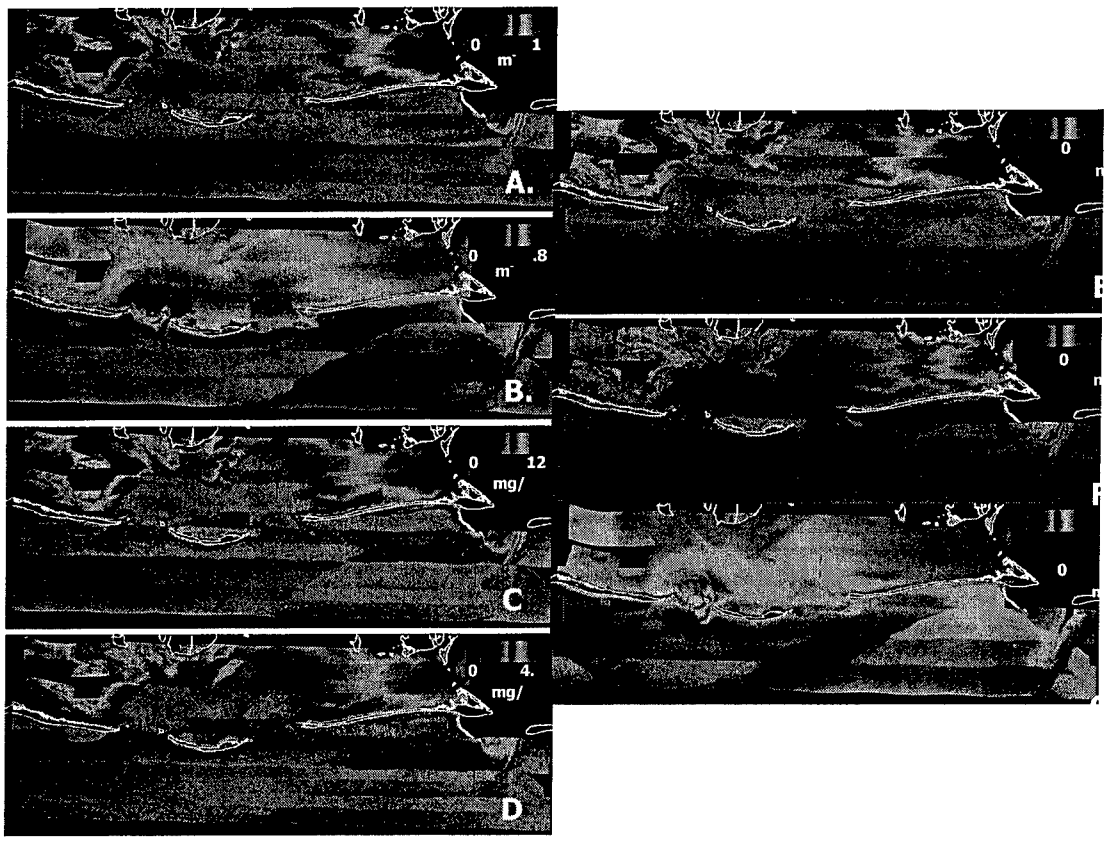

Figure 5. PHILLS flight line mosaics for 21 May. A. bi(555). B. bo(555). C. PIM concentration. D. POM concentration. E. $a_g(412)$. F. $a_d(412)$. G. $a_\phi(443)$.

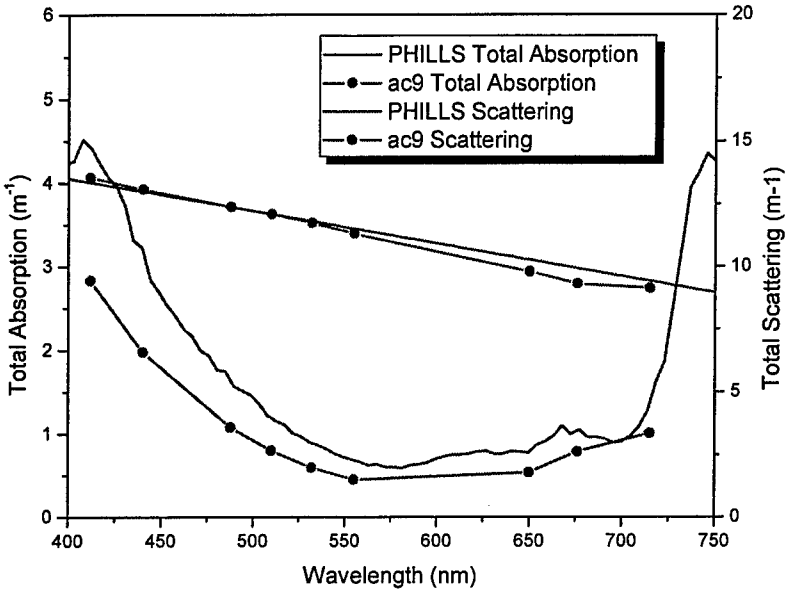

Figure 6. Total absorption and scattering coefficients vs. wavelength, PHILLS-derived and ac9-measured, R/V Ocean Color station 1 on 21 May.

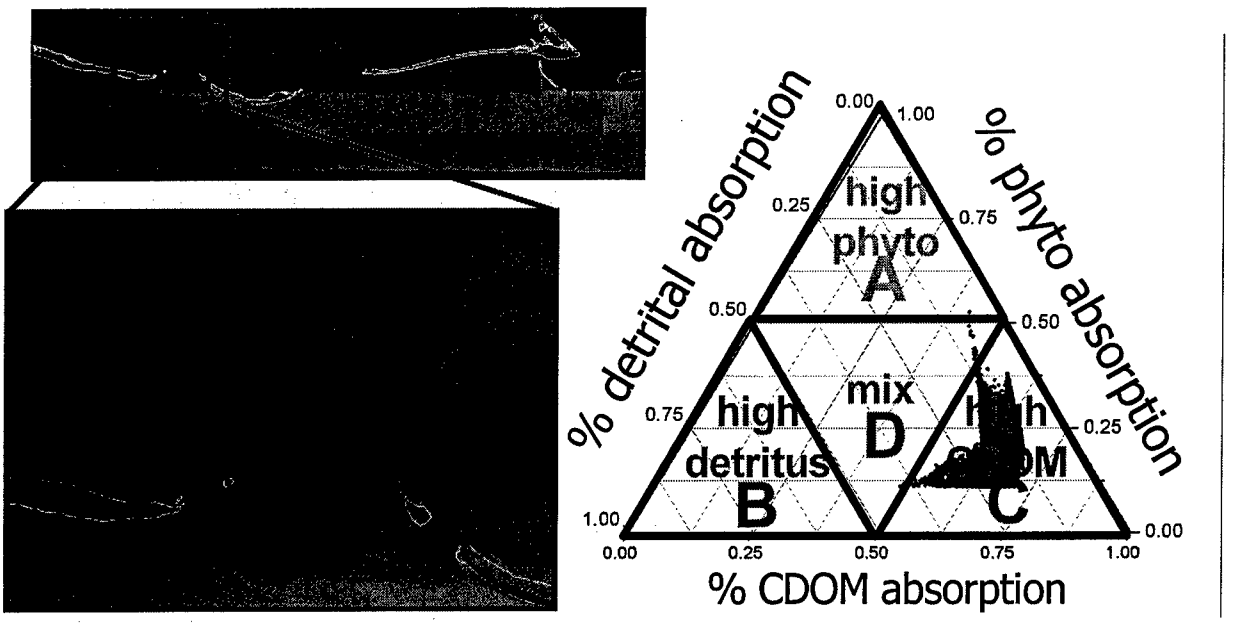

Figure 7. Optical water mass classification for PHILLS imagery, 19 May. RGB composite image with $\%a_d(412)$) loaded in the red channel, $\%a_\varphi(443)$ loaded in the green channel, and $\%a_g(412)$ loaded in the blue channel. The black points clustered in the lower right corner of the ternary diagram indicate that although there is some variability, CDOM absorption dominates the total absorption signal in this region.

DISCUSSION AND SUMMARY

We have presented new algorithms to estimate backscattering and absorption coefficients from hyperspectral ocean color imagery; based on spectral R_{rs} at NIR wavelengths. Empirical relationships are used to partition the absorption coefficient into phytoplankton, detrital, and CDOM components, and these components are ultimately used in an optical water mass classification scheme. These approaches were applied to high-resolution (10 m pixels), hyperspectral aircraft imagery collected near Mobile Bay, Alabama. Several sources of error contribute to the overall agreement between PHILLS estimates and ship measurements:

1. PHILLS sensor calibration
2. Empirical Line Calibration method – incorrect R_{rs} estimates
3. Non-negligible CDOM, detrital, or pigment absorption at NIR wavelengths
4. C term incorrect or not constant
5. Incorrect shape of spectral $b(\lambda)$ or $b_b(\lambda)$
6. Incorrect or variable $b_b(\lambda)/b(\lambda)$ ratio (i.e., variable volume-scattering function between stations)

We are exploring these error sources further, but initial results show good agreement between PHILLS-derived values and ship measurements (both R_{rs} and optical properties). The optical water mass classification technique (RGB imagery and ternary plots) helped delineate patterns in the absorbing characteristics of the waters in and around Mississippi Sound, and indicated that CDOM dominates absorption in this region.

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